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- We look at intraplate deformation and inherited structures
- We analyze different patterns related to crustal structures
- Results indicate the importance of the mantle lithosphere

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- Supporting Information S1

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Inherited structure and coupled crust-mantle lithosphere evolution: Numerical models of Central Australia

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Abstract Continents have a rich tectonic history that have left lasting crustal impressions. In analyzing Central Australian intraplate orogenesis, complex continental features make it difficult to identify the controls of inherited structure. Here the tectonics of two types of inherited structures (e.g., a thermally enhanced or a rheologically strengthened region) are compared in numerical simulations of continental compression with and without “glacial buzzsaw” erosion. We find that although both inherited structures produce deformation in the upper crust that is confined to areas where material contrasts, patterns of deformation in the deep lithosphere differ significantly. Furthermore, our models infer that glacial buzzsaw erosion has little impact at depth. This tectonic isolation of the mantle lithosphere from glacial processes may further assist in the identification of a controlling inherited structure in intraplate orogenesis. Our models are interpreted in the context of Central Australian tectonics (specifically the Petermann and Alice Springs orogenies).

1. Introduction

Inherited structures in the crust have long been recognized as playing a role in plate tectonics [e.g., *Wilson*, 1966], especially in the breakup of continents [*Huismans and Beaumont*, 2003; *Gueydan et al.*, 2008; *Buiter et al.*, 2009; *Précigout and Gueydan*, 2009; *Burov*, 2010; *Gueydan et al.*, 2014; *Bercovici and Ricard*, 2014]. However, the genesis of intraplate crustal deformation related to far-field compression has been difficult to quantify and characterize [e.g., *Ranalli*, 1995], especially in Central Australia where a basin inversion may have taken place. The study of basin inversion (i.e., where sedimentary basins formed by rifting are compressed) has generated a number of mechanisms for deformation within a plate interior, including preexisting crust and mantle structures, the presence of fluids, the burial of highly radiogenic material and other temperature anomalies, compositional strengthening, and strain rate [e.g., *Ziegler*, 1987; *Ziegler et al.*, 1995, 1998; *Sandiford*, 1999; *Nielsen and Hansen*, 2000; *Hansen and Nielsen*, 2002; *Sandiford et al.*, 2006; *Stephenson et al.*, 2009; *Gorczyk et al.*, 2013; *Gorczyk and Vogt*, 2015; *Regenauer-Lieb et al.*, 2015]. In this paper we compare the tectonic evolution of two types of inherited structure, and apply these findings to the discussion of Central Australian intraplate orogensis.

North-south compression in Central Australia, related to Pangean plate tectonics, is associated with two major intraplate deformation events: the Petermann orogeny (late Neoproterozoic to Early Cambrian, 570–530 Ma) and the Alice Springs orogeny (Devonian to Carboniferous, 370–300 Ma) [e.g., *Forman*, 1966; *Shaw and Black*, 1991]. Figure 1 shows the areas of orogenesis and the major tectonic blocks of this region, namely, the Amadeus basin (a remnant of the Centralian Superbasin [*Walter and Gorter*, 1994; *Walter et al.*, 1995]) with Petermann and Alice Springs orogenies on its margins, and the Arunta and Musgrave blocks (which amalgamated to Central Australia in the Mesoproterzoic (∼1100 Ma) [*Myers et al.*, 1994; *Shaw et al.*, 1996]). Numerous studies infer that the extensional tectonics of the Centralian Superbasin (∼800 Ma) had a significant rheological impact on the region, in particular, due to sediment deposition [e.g., *Korsch and Lindsay*, 1989; *Shaw and Black*, 1991; *Walter et al.*, 1995; *Hand and Sandiford*, 1999; *Braun and Shaw*, 2001]. The subsequent compression of the region generated little crustal deformation within the interior of the Amadeus basin, with thrust faults and lower crust exhumation of the Petermann and Alice Springs orogenies localized on the Amadeus margins (Figure 1b).

Here we investigate two thoughts on the mechanisms of intraplate deformation and compare quantitatively their tectonic evolution in numerical models: (1) the interior of the Amadeus basin is a rheologically

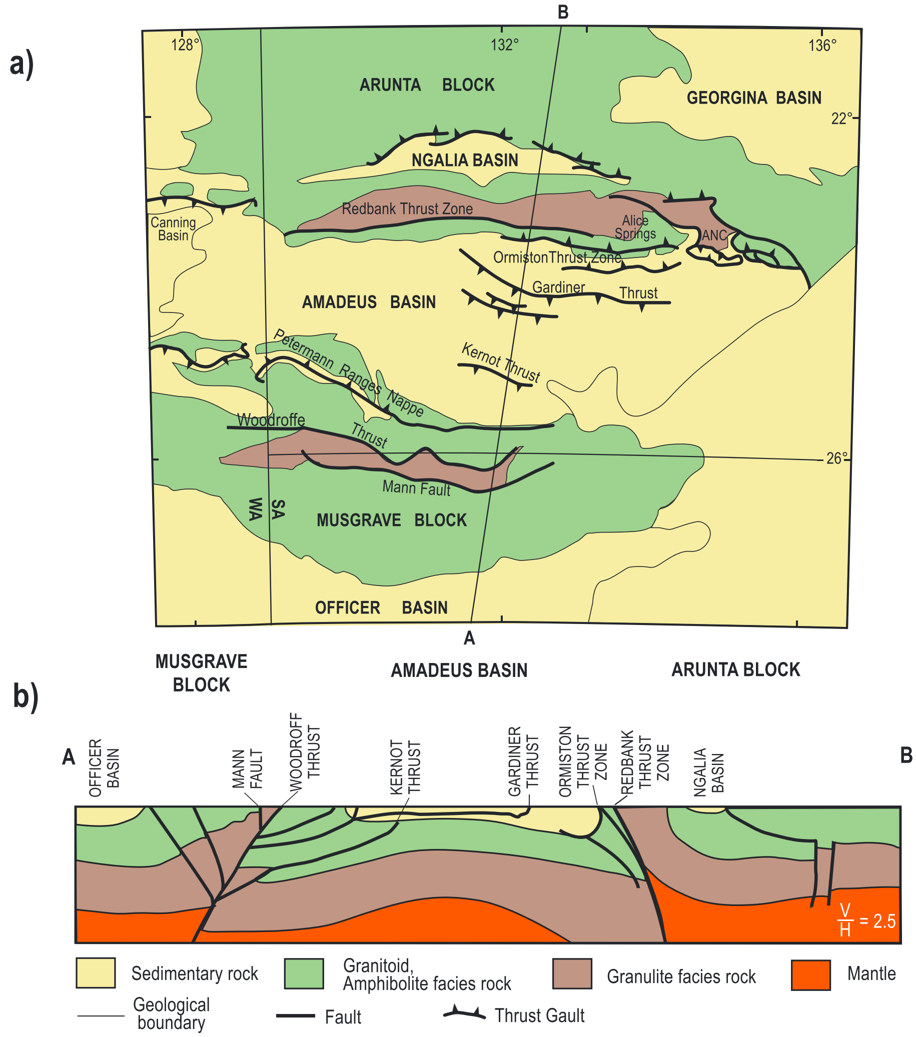

Figure 1. (a) Geological map and (b) interpretative cross section showing crustal scale structure features in central Australia from *Shaw et al.* [1991] and (modified from *Roberts and Houseman* [2001]).

strengthened crustal region with respect to the surrounding blocks owing to the age of the craton [*Braun and Shaw*, 2001]; (2) the burial of sediments during basin development generated a highly radiogenic layer on the margins of the Amadeus basin, leading to high surface heat flux and thermal weakening [*Sandiford and Hand*, 1998; *Hand and Sandiford*, 1999; *Gorczyk and Vogt*, 2015].

Although a number of different mechanisms for the tectonic evolution of Central Australia have been proposed, numerical simulations of the region have imposed contrasting rheological conditions related to the basin inversion processes. In thin viscous sheet models, the Amadeus basin has either been modeled as a weak region due to its high surface heat flux [e.g., *Roberts and Houseman*, 2001] or with strengthening in its interior because of the craton age [e.g., *Braun and Shaw*, 2001]. Our models differ from previous studies by contrasting the deformation patterns of two distinct types of inherited structures and by allowing for a full appraisal of the dynamics of the mantle lithosphere (which is difficult in thin viscous sheet models [e.g., *Braun and Shaw*, 2001; *Roberts and Houseman*, 2001]). The burial of radiogenic sediments (e.g., one of our inherited structures for the region) has been shown to significantly impact tectonic activity through Rayleigh-Taylor instabilities in the mantle lithosphere [e.g., *Pysklywec and Beaumont*, 2004; *Gorczyk et al.*, 2013; *Gorczyk and Vogt*, 2015]. Based on previous hypotheses of a thermal anomaly [e.g., *Sandiford and Hand*, 1998; *Hand and Sandiford*, 1999], it is appropriate to relate crustal deformation in Central Australia orogenesis to the deeper lithosphere [e.g., *Gorczyk et al.*, 2013; *Gorczyk and Vogt*, 2015]. Our study offers the first comparison of deformation

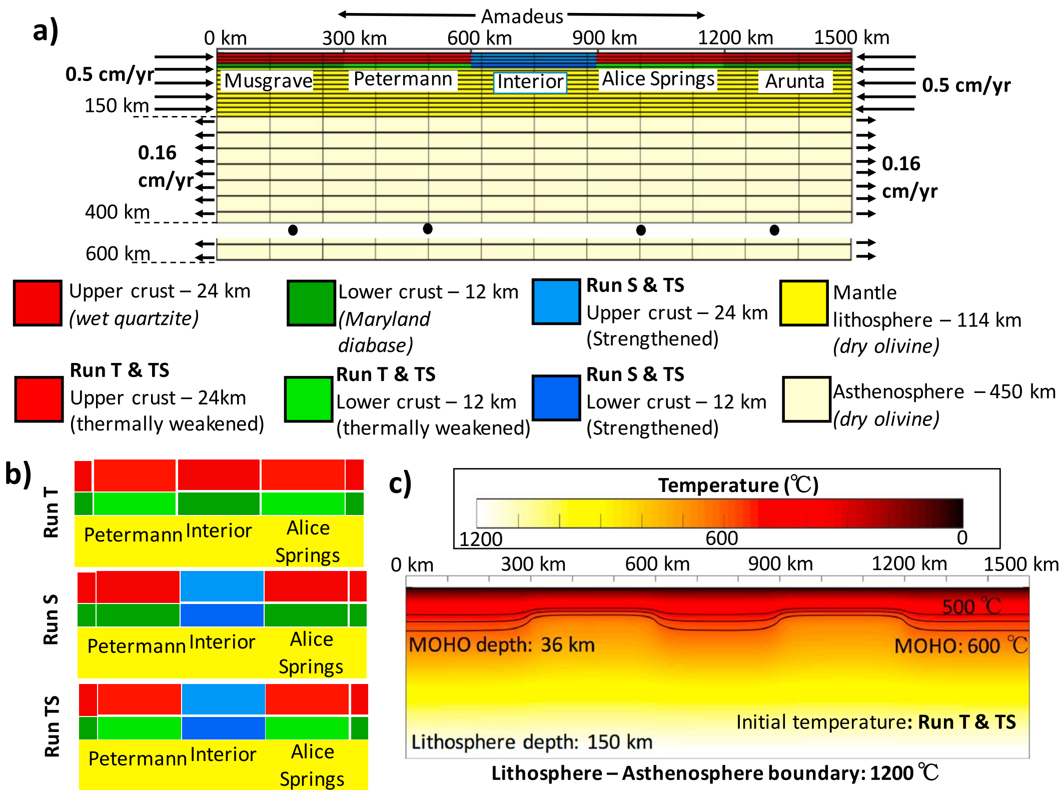

Figure 2. The initial setup of the model runs. (a) The material field denoting the different rheological layers. Model run TS is shown, with the upper and lower crust of the Arunta and Musgrave blocks thermally weakened and the upper and lower crust of the Amadeus block rheologically strengthened. (b) Cartoon of color coordination of Runs T, S, and TS (with same legend as in Figure 2a). (c) Initial temperature field for the thermally enhanced models (e.g., Runs T and TS). For Run S, the initial Moho temperature is 600°C across the model. Rheological parameters follow *Gleason and Tullis* [1995] for upper crust (with scaling factor f = 0.3); *Ranalli* [1997] and *Mackwell et al.* [1998] for lower crust (f = 0.05); *Hirth and Kohlstedt* [1996] and *Kawazoe et al.* [2009] for mantle (f = 0.3).

for two different drivers of intraplate orogenesis featuring detailed numerical modeling of the mantle lithosphere of the region.

Paleo-erosion rates for Central Australia are not clear; glaciation has been hypothesized for the time frame [*Powell*, 1984; *Roberts and Houseman*, 2001] and can be indicative of extreme removal of topography [*Tomkin and Roe*, 2007; *Berger et al.*, 2008; *Thomson et al.*, 2010]. In order to assess the response of the lithosphere to climate-controlled processes in a glacial environment, we impose a “glacial buzzsaw” erosion law in selected models to test an end-member situation. Although such a severe erosion has only been hypothesized in Central Australia, it is appropriate for various other orogenic regions across the world [*Thomson et al.*, 2010].

In this study, we present idealized systems of the postulated inherited structures in order to understand the fundamental differences among the subsequent deformation patterns. In numerical experiments of continental shortening, the first-order deformation related to crustal strengthening and thermal weakening are analyzed with reference to existing hypotheses on Central Australia.

2. Modeling Methods

Continental shortening is modeled using SOPALE, a two-dimensional plane strain numerical code that solves for the deformation of high Prandtl number incompressible viscous-plastic media [*Fullsack*, 1995]. We solve the conservation equations of mass, momentum, and energy in a 600 × 1500 km model space (401 × 217 Eulerian grid and 801 × 649 Lagrangian mesh, with maximum Lagrangian grid resolution of 0.3 × 3 km in the crust). Figure 2a shows our initial setup of continental block configuration with rheological units defined by color. Our simplified model of the Amadeus block is defined by 900 km in width and separated into three equally spaced regions: the pre-Petermann orogeny region; the interior block of the Amadeus; and the pre-Alice Springs region. A convergence of 0.5 cm yr^{-1} is applied to both sides of the lithosphere, with corresponding escape flux applied to the asthenospheric sides. In keeping with the inferred configuration of the continental lithosphere of Central Australia, we initially apply a "jelly sandwich" type rheology [*Hand and Sandiford*, 1999; *Sandiford et al.*, 2001; *Aitken et al.*, 2009] with a strong mantle lithosphere supported by a weaker lower crust. Initially, a linear temperature increase of 20°C to 600°C from the surface to the Moho depth (36 km) is imposed, with a further linear temperature increase to 1350°C at the base of the model (and 1200°C at the lithosphere-asthenosphere boundary). Radiogenic heat production is applied to the crust, with the majority of internal heat generation coming from the upper crust (2.1 $\mu W\ m^{-3}$) [e.g., *Beaumont et al.*, 2004] rather than the lower crust (0.7 $\mu W\ m^{-3}$).

To test two differing theories on the generation of intraplate deformation in Central Australia we set up three idealized models (Figure 2b): a model where the crust of the pre-Petermann and Alice Springs regions (the margins of the Amadeus block) are thermally weakened (Run T), akin to the theories presented by *Sandiford and Hand* [1998]; a model where the interior of the Amadeus block is rheologically strengthened (Run S), similar to models presented by [*Braun and Shaw*, 2001]; and a model where the Amadeus block is both rheologically strengthened (in its interior) and thermally weakened (on its margins) (Run TS). The Amadeus interior is rheologically the same as the Arunta and Musgrave blocks in Run T, while the Petermann/Alice Spings regions are rheologically the same as the Arunta and Musgrave blocks in Run S (Figure 2b).

In Run T (and TS), a deep radiogenic source is buried to model a process possibly involved in basin deposition in Central Australia [e.g., *Sandiford and Hand*, 1998; *Hand and Sandiford*, 1999]. Figure 2c shows the initial thermal structure for Runs T and TS after a period of thermal equilibration where the thermal state of the model was advanced while preventing material motion (i.e., thermal advection) [e.g., *Pysklywec and Beaumont*, 2004]. The Moho temperature in the thermally enhanced regions is 100 K greater than within the Amadeus interior and Musgrave/Arunta provinces, while an increase in surface heat flow of 13% is also found. In Run S, the effective viscosity of the upper and lower crust of the Amadeus interior (blue regions in Figures 2a and 2b) is increased by a factor of 2 in comparison with the surrounding material in order to model an old, strong cratonic region beset by younger continental crust [*Braun and Shaw*, 2001].

For all models we apply an end-member erosional case to simulate hypothesized glaciation in the region [*Powell*, 1984; *Roberts and Houseman*, 2001]. The "glacial buzzsaw" describes the observation that summit elevations match glacial equilibrium line altitudes (ELA) in active mountain ranges [e.g., the Andes *Broecker and Denton*, 1990; *Thomson et al.*, 2010]. In this case, once an orogen's elevation passes through the ELA, high erosion rates due to glaciation act to remove any excess topography. For the Andes, the ELA is affected by latitude in that the snowline is at a lower topography as the orogen moves toward the South Pole [*Broecker and Denton*, 1990]. To accommodate the latitude positioning of the Central Australian orogenies (while taking into consideration the subdued topography of the models), we impose a (modest) topographic maximum (i.e., ELA) of 1000 m to all the models (Runs T, S, and TS). Deposition is implemented and follows *Gray and Pysklywec* [2012].

3. Results

We present results from 6 model runs (Run T, S, and TS with the corresponding glacial erosion models that feature a limiting topography of 1 km) to examine the difference in deformation of inherited structures when shortened. Figure 3 shows the rheologic blocks (top) and visualization of the second invariant of the deviatoric strain rate tensor (bottom) to indicate active deformation and zones of localization. We compare snapshots of the simulations after significant shortening (300 km), which are indicative of the style of deformation of the model run.

Enhancing the crustal radiogenic heating (Run T) generates deformation on the margins of the Petermann and Alice Springs upper crust (Figure 3a). The lower crust deformation in Run T controls the upper crust tectonics as the thickening of the layer during compression splays onto the upper crust, generating thrusting on the margins of the Petermann and Alice Springs regions (as shown by the stain rate plots) but also the interior of the Amadeus. The interior of the Petermann and Alice Springs upper crust remains relatively undeformed. At depth, the high strain rate in the mantle lithosphere is below the thermally enhanced regions. Away from the Petermann and Alice Springs areas, the mantle lithosphere is relatively undeformed.

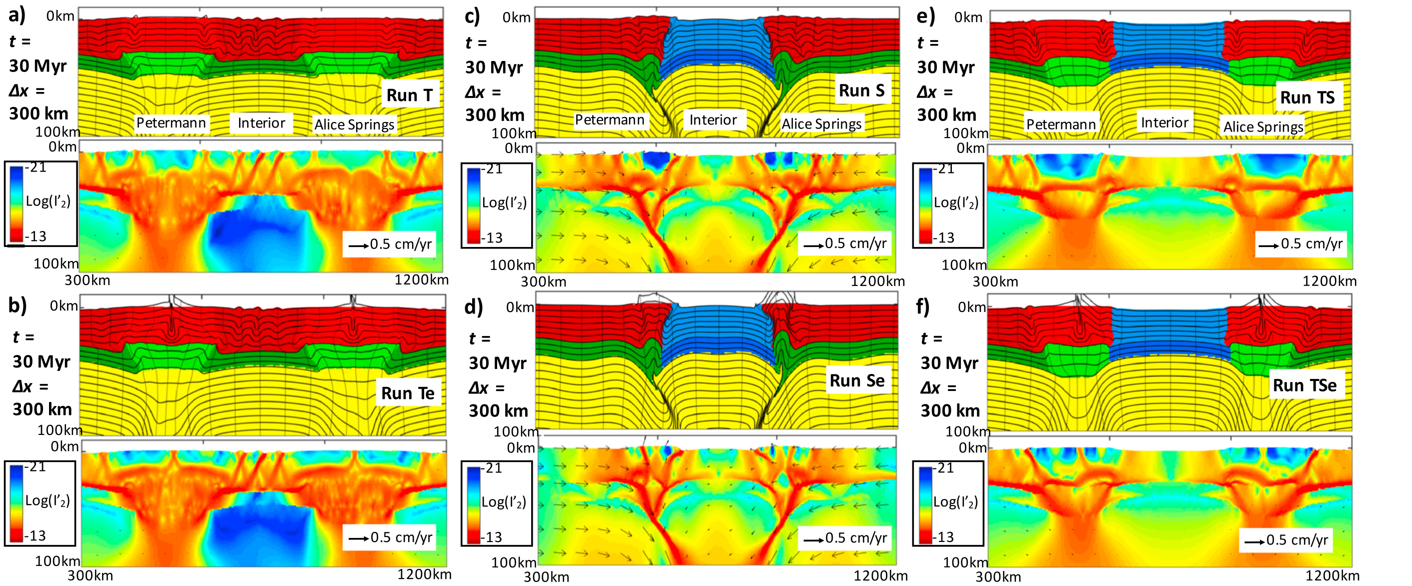

Figure 3. (top) Material deformation and (bottom) visualization of the second invariant of the deviatoric strain rate tensor after shortening for (a) Run T (with thermally enhanced Petermann and Alice Springs crust); (b) Run T with glacial erosion; (c) Run S (with rheologically strengthened Amadeus interior crust); and (d) Run S with erosion; (e) Run TS (with thermally enhanced Petermann and Alice Springs crust and rheologically strengthened Amadeus interior crust); and (f) Run TS with glacial erosion. A 3X vertical exaggeration has been applied.

The results from Run T have been replicated with varying degrees of thermal enhancement (in results not shown here), and indicate a specific mechanism related to the burial of radiogenic material and the warming of the Moho. Namely, the weakened interior of an enhanced thermal interior does not deform as readily as the material in contact with the thermal contrast (Figure 3a). Furthermore, the tectonic activity related to the crustal thermal anomaly is not confined to the near surface. The broad high strain rates in the mantle lithosphere indicate deeper tectonic processes [e.g., *Pysklywec and Beaumont*, 2004].

The application of glacial erosion to Run T (e.g., Run Te, Figure 3b), where any topography above 1 km is removed and deposited into basins, simplifies the deformation pattern. Although faulting within the Amadeus interior is more pronounced, the deformation related to the upper crust margins of the thermally enhanced regions disappears. The glacial erosion localizes all deformation in the thermally enhanced regions to its center, producing tight thrusting in the upper crust (Figure 3b). However, the broad high strain rate pattern in the mantle lithosphere is not impacted by the glacial erosion.

The strengthening of the Amadeus interior when compared to the surrounding rheologies [e.g., *Braun and Shaw*, 2001] generates an interior basin and deformation on its margins (linked to the strength contrast) (Figure 3c). The deformation is localized to the Petermann and Alice Springs regions, with exhumation of the lower crust generating folding in the upper crust. The Amadeus interior undergoes no internal deformation, but does exhibit some crustal flexure related to larger-scale mantle lithosphere bending. Deformation within the mantle lithosphere is confined to narrow bands of mantle shearing (as shown in the strain rate figures) generating crustal flexure. The application of glacial erosion to this rheologic setup further localizes the deformation to the Amadeus interior boundary (Figure 3d). This in turn enhances the uplift and exhumation of the mid and lower crust. Again, the deformation of the mantle lithosphere is unchanged with the addition of glacial erosion.

Figure 3e shows the results from Run TS, a combination of the setup of both Runs T and S. All the crustal deformation occupies the margins of the thermally enhanced Petermann and Alice Springs regions. The Amadeus interior, in contrast to Run T, remains undeformed, while the flexure of the crust (as seen in Run S) does not materialize. Instead, the mantle lithosphere deformation occurs beneath the Petermann and Alice Springs regions (Figure 3e).

The application of glacial erosion to Run TS (Figure 3f) shows a localization of the deformation as in Run Te and Run TSe. However, for Run TSe (when compared to Run TS) the main thrust faults on the margins of the Amadeus interior are shifted to the center of the thermally enhanced region. The deformation is localized

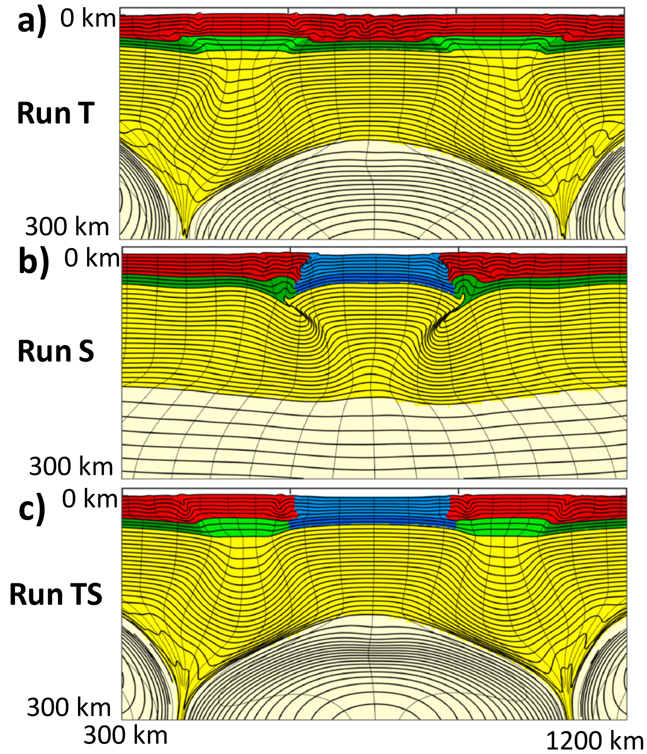

Figure 4. Material deformation for the whole lithosphere after shortening for (a) Run T, (b) Run S, and (c) Run TS (as presented in Figure 3). A 1.33X vertical exaggeration has been applied. The thermally enhanced crust has an impact on the mantle lithosphere to produced dripping in Figures 4a and 4c.

into two distinct faults either side of the interior, highlighted by strong decoupling of the upper and lower crust (indicated by high strain) (Figure 3f). However, at depth the glacial erosion does not change deformation patterns.

4. Discussion and Conclusions

In this study we have presented intraplate deformation related to two different inherited structures postulated for Central Australia. By applying shortening to a model with two thermally enhanced regions (Run T) and a model with a rheologically strengthened region (Run S), distinct deformation patterns are produced. The crustal deformation of Run T is limited to the margins of the thermally enhanced region and the interior of the nonthermally enhanced region (Figure 3a). Run S deformation is localized to the margins of the strengthened block (Figure 3c). Runs T and S are similar in that deformation is not pronounced in the interior of the anomalous region. However, the application of glacial erosion to Run T shifts the deformation pattern and localizes it in the center of the thermally enhanced zone (Figure 3b). In both Runs T and S, the mantle lithosphere bends beneath the thermally or rheologically affected zones.

Despite our inherited structure being of crustal origin, the mantle lithosphere is important in controlling the evolution of deformation [e.g., *Calignano et al.*, 2015]. Figure 4 extends the material plots of Figure 3 to include the whole of the lithosphere. The models that feature thermal anomalies (Runs T and TS) generate lithospheric dripping [e.g., *Pysklywec and Beaumont*, 2004] (Figures 4a and 4c). The impact of a strengthened crust on the mantle lithosphere (e.g., Run S) is minimal (Figure 4b).

The combination of Runs T and S into Run TS does not fully generate deformation that is a superposition of the two (Figure 3e). The crustal deformation can be seen to be formed at the margins of the thermal and strength contrasts (following a superposition principle). However, the crustal flexure in the interior as shown in Run S is not as pronounced in Run TS, while mantle lithosphere folding is predominately that of Run T (Figure 3e). This pattern can be explained in Run TS by the thermal contrast in the subcrust (i.e., Figure 3b) and the failure of the lower crust to produce exhumation (e.g., Figure 3c). To that end, Run TS is not a superposition of patterns related to the two separate inherited structures, and the dominant thermal anomalies impacting the behavior of the mantle lithosphere dominate crustal tectonics [e.g., *Heron et al.*, 2016].

Our models are idealized in terms of the evolution of Central Australia, and an attempt to match the crustal evolution of the region would be unrealistic due to the general nature of the study. However, comparing our findings to a simplified view of Central Australia's intraplate orogenesis is a worthwhile contribution to further understand the area. The discussion of the differences in deformation generated by these two distinct inherited structures has not been previously looked at in such high-resolution numerical studies and to a depth of the mantle lithosphere, despite being previously highlighted as possible mechanisms for intraplate deformation in the region [*Sandiford and Hand*, 1998; *Hand and Sandiford*, 1999; *Braun and Shaw*, 2001].

The deformation pattern of Central Australia can be characterized as showing exhumation of the lower crust, flexure of the crust and mantle lithosphere, and limited deformation within the Amadeus interior with thrust faulting on its margins (Figure 1b). Addressing these features, Run S presents the strongest case in our limited suite of models (Figure 3c). The thermal enhancement of the Petermann and Alice Springs regions (Run T) fails to develop all but one of these characteristics (with deformation on the margins of thermal regions being generated) (Figure 3a). Run TS follows Run T, but with the preferable addition of no deformation within the Amadeus basin (Figure 4a).

Although all models show some crustal characteristics of the region, it is the mantle lithosphere where differences are clear. If deeper imaging of the region became available, our modeling results show that the consideration of mantle lithosphere deformation would better understand the evolution of the intraplate event(s). In the context of previous interpretations, evidence of lithospheric Rayleigh-Taylor dripping could help bolster the hypothesis that buried radiogenic material could have developed intraplate deformation [e.g., *Sandiford and Hand*, 1998; *Hand and Sandiford*, 1999].

The application of a "glacial buzzsaw" is an extreme method of erosion but one that might be applicable to the region [*Powell*, 1984; *Roberts and Houseman*, 2001]. The results here reconcile with previous work on climate and crustal tectonics in that the modification of crustal mass flux by surface denudation can change the evolution of an orogen by constraining its width [e.g., *Willett*, 1999]. In Run Te and Run TSe, the patterns were localized but also shifted. However, Run S, our preferred model, found only localization of deformation.

Our glacial buzzsaw results differ with previous studies in that its erosional impact does not impact the sub-crustal lithosphere [e.g., *Pysklywec*, 2006]. Despite extensive amounts of shortening, changes in deformation by imposing a limit to topography through glaciation (1 km) are confined to the crust (Figure 3). Erosion in continental collisions can have a significant impact on the deeper lithosphere [e.g., *Pysklywec*, 2006], adding further to the tectonic complexity of intraplate orogenesis. Future work on glacial regions could focus on the role of erosion on the generation of the intraplate orogenesis, with further constraints paleo-climate required to promote any hypothesis for Central Australia.

Previous numerical modeling of the region has concentrated on thin viscous sheet simulations and not the deeper lithosphere [e.g., *Roberts and Houseman*, 2001; *Braun and Shaw*, 2001], or simulations focusing on Rayleigh-Taylor instabilities from plume-based thermal anomalies [e.g., *Gorczyk et al.*, 2013; *Gorczyk and Vogt*, 2015]. However, the coupling between crust and mantle lithosphere in intraplate tectonics has been shown to be important here. Future models on the evolution of Central Australia would benefit from a more detailed analysis of the processes by which the inherited structures were generated (which is beyond the scope of this study). Simulations that span the time frame from the amalgamation of the Arunta and Musgrave blocks in the Mesoproterzoic (~1100 Ma) [*Myers et al.*, 1994; *Shaw et al.*, 1996], to the eventual two-stage shortening processes that formed the Petermann (late Neoproterozoic to Early Cambrian, 570–530 Ma) and the Alice Springs orogeny (Devonian to Carboniferous, 370–300 Ma) [e.g., *Forman*, 1966; *Shaw and Black*, 1991] would help to understand which processes become dominant over time. In this study we impose inherited structures. However, an ideal numerical analysis would allow for a more dynamic process of inheritance [e.g., *Regenauer-Lieb et al.*, 2015].

The processes involved in the generation of intraplate orogenesis within Central Australia have been inferred to be related to the presence of inherited structures that caused localized deformation [*Sandiford and Hand*, 1998; *Hand and Sandiford*, 1999; *Braun and Shaw*, 2001; *Gorczyk et al.*, 2013; *Gorczyk and Vogt*, 2015; *Regenauer-Lieb et al.*, 2015]. Through simplifying the mechanisms of deformation to be related to either thermal or rheological inheritance in the crust, we present distinct differences in the evolution of the region (in particular, within the mantle lithosphere). Furthermore, the application of erosion related to glacial coverage (hypothesized for the region [*Powell*, 1984; *Roberts and Houseman*, 2001]) showed deformation changes confined to the crust. This tectonic isolation of the mantle lithosphere from glacial processes may further assist in the identification of a controlling inherited structure in intraplate orogenesis (e.g., Figure 4). Our results indicate that not only crustal but also mantle lithosphere deformation could be important in helping to classify the complex nature of intraplate orogenesis.

Acknowledgments
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